Experiences in Monitoring and Modeling Sediment Discharge from Todoroki Watershed and Its Implications for Management of Shiraho Reef Area in Ishigaki Island, Okinawa Japan

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1. INTRODUCTION AND OBJECTIVES

Corals are currently subject intense stresses from environmental disturbances arising from inland activities; a case in point is sedimentation. Prominent mainly to fringing reef areas, eroded soil materials from adjoining inland sources conveyed through rivers and transported in littoral suspension eventually settle on the different locations on the reef. Sediment supply from terrestrial sources is chiefly driven by strong outflows especially during typhoon events or extreme rainfall conditions. Short-term sedimentation negatively affect photosynthetic activity of coral symbiotic algae, zooxanthellae (Philipp and Fabricius, 2003) but prolonged suspension and excessively thick burial can lead to coral mortality although occurring at different times scales; some species die within few hours while others exhibit some degree of tolerance (Wesseling et al., 1999; 2000). Sediment burial of reef substrate also reduces suitable sites for coral larvae settlement, hence hampering even coral reproductive capability. The sedimentation problem is peculiarly interesting to the science, monitoring, conservation and management aspects of coral reef environment since it is regarded as a clear form of direct anthropogenic disturbance resulting from terrestrial activities, mainly thru deforestation of upland areas, cultivation of agricultural fields, and infrastructure development.

This case study provides an account of our experience in developing a monitoring and method and modeling technique to determine the extent and magnitude of sediment discharge from a given catchment system. Details of the field monitoring components of sediment discharge assessment and resource requirements for building the overland erosion and sediment discharge model are described. This paper documents information not necessarily pertinent to research objectives and scientific goals of the investigators, but more specifically, attempts to inform managers and decision makers on how erosion and sedimentation is assessed on a per watershed basis and their addresses issues related to their implementation The perspective comes from that of a university research group. Generally, it seeks to contribute towards establishment and institutionalization of effective monitoring systems in as part of broader attempts to generate baseline data against which the impacts of natural and anthropogenic changes can be measured.

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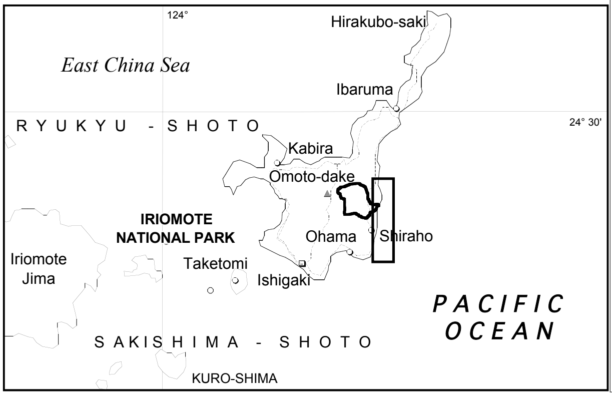
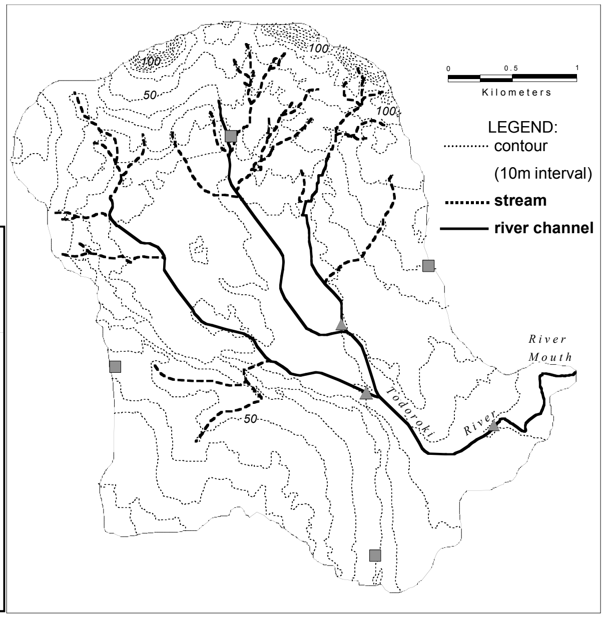
Fig 1. The studya rea. Below: location of the Todoroki watershed and the Shiraho Reef area. Right: The Todoroki watershed and location of rain gauge stations (squares) and turbidity sensors (triangles).





2. MONITORING ACTIVITIES

Physical characteristics of study area

Ishigaki island is located about 24°23' N latitude, 124°14' E longitude, 430 kms southwest of the main Okinawa island. The climate in Ishigaki is subtropical, with the annual mean temperature, relative humidity and precipitation being 24.3°C, 78%, and about 2,000 mm, respectively. Two rainy seasons occur, monsoon (March to May) and typhoon (July to September). Wind directions are dominantly southerly in summer and northerly in winter. A catchment draining to the Todoroki River has been delineated with a size of about 11.5 km^2. Slope varies from 0 to 17% with elevation ranging from 0 to 149 m. The main crops grown in the clay-loam soil dominated area are pineapple (*Ananas comosus* Merr.), rice, tobacco and sugarcane (*Saccharum officinarum* L.) with few isolated built structures such as farmhouses, granaries and ranches. Other agriculture-based industries like cattle raising and vegetable farming are also present in the area and are likewise tagged potential culprits for further soil degradation. Overall, the study area can be characterized as mixture of land uses and varying topography and climatic conditions that makes it an ideal case for studying erosional events.

Researcher's motivation and issues in study area

The fringing Shiraho Reef, Ishigaki Island (Okinawa, Japan) serves as a rich coastal resource and popular ecotourism destination among Japanese and neighbouring countries. Previously, the researchers were involved with monitoring the hydrodynamic and thermal aspects of reefs in Shiraho region (Nadaoka, *et al*, 2001a, 2001b) to supplement knowledge on reef environment responses to massive bleaching and extreme events such as typhoons. Sedimentation has been identified as one of the primary causes of coral degradation in the narrow-strip longitudinal (8 km x 0.5 km) Shiraho Reef. Although corals such as *Porites* spp., *Montipora* spp., *Acropora* spp., and *Heliopora coeruelea* flourish and free of macroalgal cover, inner reef corals are smothered with terrestrial sediments and suffer from presence of dense macroalgae. Initial assessment determined that river discharge turbidity levels often reach excessive values and deflects towards inner parts of the reef. From studies relating to the distribution (Omija et al., undated) and transport patterns of sediments on the reef area, it became apparent that quantifying the amount as well as the dynamics of sediment discharge from the land area adjacent would also prove useful in understanding reef ecological responses of the reef subject to anthropogenic disturbances. There had been reported strong correlations between estimated inland erosion channeled through the Todoroki River from its catchment area and the amount spreading through the reef. In 2001 alone , there was a mass mortality of *Porites* corals caused by heavy runoff of red clay soil and fresh water from Todoroki River on Ishigaki Island. More than 75% of corals died in the area and the mortality was over 25% in an area near the river. Activities within the Todoroki watershed, mostly agriculture-based were identified as potential contributors to erosional process. Thus, conflicts of interest between land- and sea-based industries inevitably arise out of the dilemma between the need to produce fundamental agricultural products against the exigency to conserve the reef and assure adequate supply of fish or fishery products. Recently, controversies loom regarding the plans for building a new airport with larger aircraft capacity intended to attract more tourists as it is intended to be constructed within the Todoroki catchment. Environmentalists raise alarm on fears that the construction will release more sediment and damage the reefs.

Table 1. Summary of field survey data characteristics.

Type of Data	Instrument and Manufacturer	Quantity	Sampling frequency	Deployment period
Data-logged				
Rainfall intensity	RG-2, Hobo Onset Applications®	4	per 0.254 mm rainfall;	June 2000 to present
Turbidity	Alec Electronics® ATU Nephelometers	3	30 min; increased to 15 min from Sep 2000	R-3: June 2000 to present R-2 and R-3: June 2000 to Nov 2001
Water depth	Diver® Van Essen Instruments	1	10 min	Sep 2000 to Feb 2002
Water temperature	Tidbit Onset Applications	3	10 min	Sep 2000 to Feb 2002

Field surveys conducted

To measure sediment discharge along the Todoroki River, three nephelometric turbidity meters were installed along the rivers such that the sensors would be able to record turbidity from two subcatchments forked upstream of Todoroki River. Calibration of the instruments in April 2000 was conducted prior to their installation in June 2000 to relate nephelometric turbidity units (NTU) with actual sediment concentrations (mg/m^3). Suspended particle in the water was varied by manually agitating river bottom sediments and simultaneously obtaining water samples, which were preserved and transported back to Tokyo. In the laboratory, sediment concentration was measured by filtration method. Concurrent with the installation of turbidity sensor, depth and water temperature sensors with data loggers were attached to the turbidity sensor frame. To assess local meteorological conditions, four rain gauges were installed within the watershed area along roadsides and rooftops. A complete weather measurement system (Hobo Weather Station®) was mounted in the Shiraho village in September 2000 but was not durable enough to withstand the harsh weather conditions during the storm season or typhoon events in Okinawa and was eventually torn down. Soil samples were also gathered in the field and were processed in the laboratory to obtain various hydrologic parameters such as hydraulic conductivity, soil moisture, porosity, grain size and typing. Vegetation structure measures such as plant spacing, layering and leaf dimensions were also recorded. Table 1 outlines the data gathered from the field observations.

Modeling efforts

Since turbidity sensors are fairly expensive to maintain and are specialized to process, it is necessary to find other approaches to accurately quantify erosion rates and sediment yield. A feasible alternative explored was to develop a computer-based model of the erosion process and sediment transport in Todoroki River. Since initial field survey data are already available, the model was built with further refinements in landcover parameterization. With analysis of remotely-sensed satellite data, mainly from Landsat and color aerial photography, distribution of vegetation abundance within the watershed was generated. The model is envisioned to simulate overland flow and runoff by a DEM (digital elevation model)-based routing with the sediment transport component ideal for small, relatively flat, agricultural watersheds where the main processes affecting sediment yield are soil erosion by raindrop impact and overland flow while sediment transport is governed by overland and bed channel flow mechanisms. The total sediment load for the Todoroki watershed during the monitoring period was computed based on time-integrated values of continuous turbidity data. Computing hardware requirements are minimal. The computer program was encoded using a free language compiler (ActiveState® Perl) run on a Windows™-based PC with current but nonetheless ordinary specifications (Pentium 400 MHz, 256 Mb RAM). Remotely-sensed data is processed using ENVI® image processing software. The output generated by the model is displayed and color-rendered in ENVI® but other graphical software packages that can import ASCII files may also be used. Parties interested in further details of the model are referred to Paringit and Nadaoka (In press).

Table 2. Breakdown of costs involved in monitoring and modeling sediment discharge from Todoroki watershed for the first year.

Type of expense	Cost (in US$)	%Fraction of total cost	Remarks
Transportation			
Personnel travel	2550	6.26	3 times a year
Equipment freight	1269	3.12	3 times a year
Instrumentation			
Turbidity meters	19,067	46.82	3 units
Depth gauges	3,813	9.36	3 units
Temperature sensor	255	0.63	3 units
Data			
Maps (Digitized)	7,500	18.42	in CD-ROM
Satellite imagery	1,200	2.95	from RESTEC; level 1b
Aerial photography	376	0.92	12 exposures; coloured
Software	3,000	7.37	ENVI® image processing software
Hardware	1,694	4.16	Pentium III, 455 MHz
TOTAL	**40,724**	100	

*currency exchange rate used: USD1=JPY118

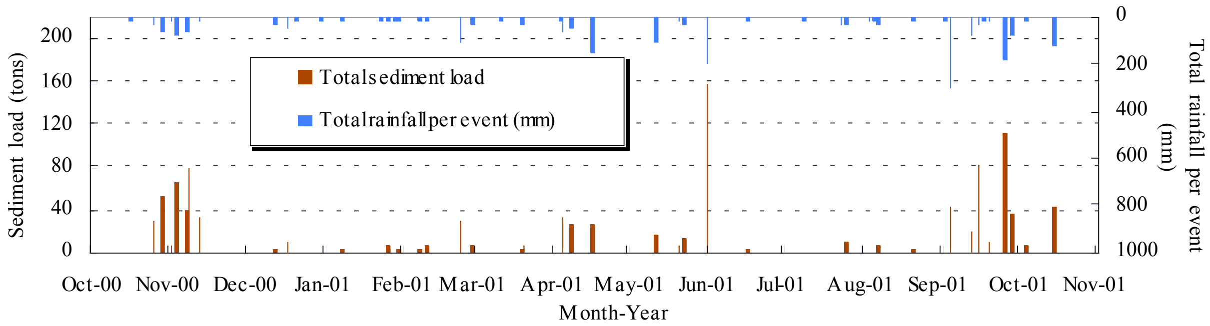


Figure 1. Distribution of sediment load. Note that higher rainfall does not necessarily correspond to higher sediment load.

3. FIELD DATA ANALYSIS AND MODELING RESULTS

Figure 1 shows the year-long rainfall and sedigraph data lumped per rainfall event. Sediment yield for the whole year was placed at 1084 tons (Oct 2000 – Oct 2001) resulting from 3.3 meters cumulative rainfall for 70 rainfall events. Results of the erosion model showed that pineapple fields contribute to the amount of soil being removed at a faster rate in proportion to the total area than all other crops. Sugarcane fields which occupies the largest area of agricultural lands follows. Overall, it was shown that soil detachment rates due to rainfall is strongly influenced not only by the fraction of vegetation it encounters but may also vary according to the type of vegetation involved and its abundance. The computed runoff and discharge shows reasonable agreement with measured discharge peaks for all rainfall events although there appears to be a lag with respect to timing. This study lent a theoretical support and empirical evidence to the role of vegetation as a potential agent for soil erosion control.

Considerations and limitations

Investigators come to Shiraho as frequent as once every three month for intensive field campaign in the reef area itself. About four months after the last deployment, the nephelometers are retrieved for data download and maintenance including replacement of the drained special 10-volt batteries and for cleaning the fouled sensor heads. The turbidity meters are then reconfigured for redeployment within days, or in some cases, just hours after retrieval. A special memory pack reader and proprietary software is needed to download data from the memory pack but may be brought to the field area for on-site processing given that ac power source is available. For a sampling interval of 15 minutes with 10-second burst (averaged), the sensors' memory pack can store about 263,000 readings equivalent to eight (8) megabit of computer memory but will be limited by the battery life which could last up to four (4) months only. On the other hand, data from rain gauges are downloaded directly from the field using a notebook PC and a set of connection interface cable and software from the manufacturer. The CR-2032 lithium battery can last for two years while the data logger has 80,000-tip event capacity equivalent to 2.03 meters of rainfall. It takes approximately half a day to do the sensor retrieval and another half a day for reinstallation. At least two persons are needed to perform the installations and redeployments. With respect to costs, there is a substantial initial capital outlay for purchase of equipment and for the establishment of computing facility but is expected to go down in subsequent years where costs are only due to maintenance.

Only archived satellite image data (Landsat 5 TM) was available used to parameterize vegetation cover was bought as a subset fraction image. Cloud cover remains a serious constraint in the use of remotely-sensed data to update land cover conditions in subtropic and humid area like Ishigaki. Statistical analysis of combined Landsat 7 ETM+ and 5 TM satellite overpasses to determine chances of getting image that is cloud-free or with acceptable cloud cover conditions show that within the past 6 years, acquisition of image are successful 48% of the time (every 16 days) and only 34% of which have lower than 25% cloud cover. As for the model performance, it took about 32 minutes to execute a 36-hour simulation. For a whole year, approximately 70 rainfall events occur with average 18-hour durations. This meteorological condition could take about 2 days of continuous albeit supervised computer processing using the model.

4. COOPERATIVE ACTIVITIES

In the course of the monitoring activities, support of governmental or government-supported environmental and research organizations were sought. Preliminary and reconnaissance field visits were conducted in the study area were accompanied by a research officer of the Okinawa Prefectural Office of Environment and Health, who also provided basic information on watershed characteristics including agricultural land use, soil type distribution based on their prior studies. A non-government organization (NGO) working on reef conservation and community awareness program in Shiraho also lent assistance. Specifically, the World Wildlife Fund for Japan (WWF-J) helped in downloading the rain gauge data when it was not possible for researchers to return to the study area. Although there is no organized effort, participation of local community were sought in the form of passive cooperation. Residents and farm owners were willing to accommodate installation of rain gauges on the rooftop of their farmhouses or on the roadside of their fields. Most of the time, fishermen act as boat people when conducting surveys on the reef area itself but certain fees were collected for boat rental. Methods of formal information dissemination and awareness regarding the use of the model are still being planned.

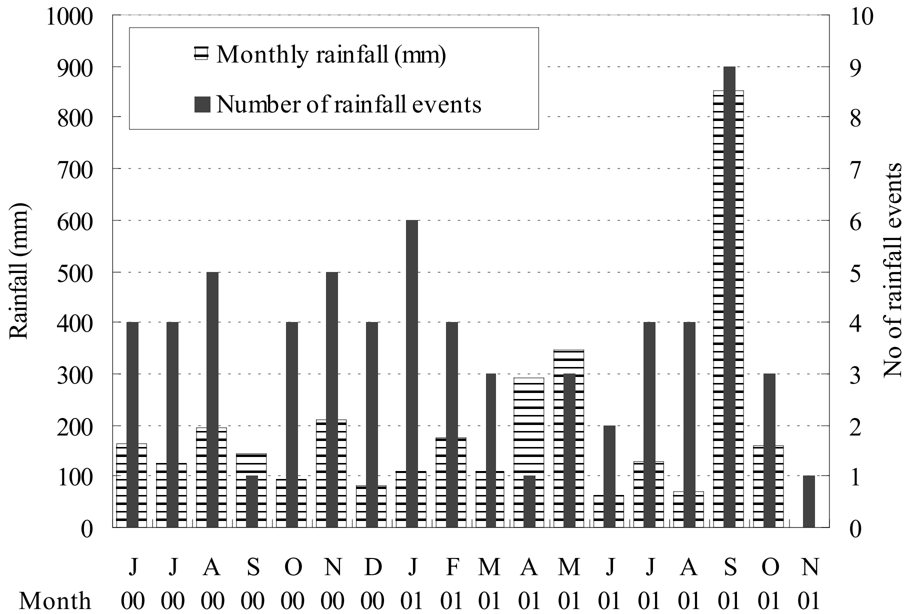


Figure 2. Aggregated rainfall and number of rainfall events per month. Disproportionate levels (i.e. when there are few events as there are higher rainfall in a given month.

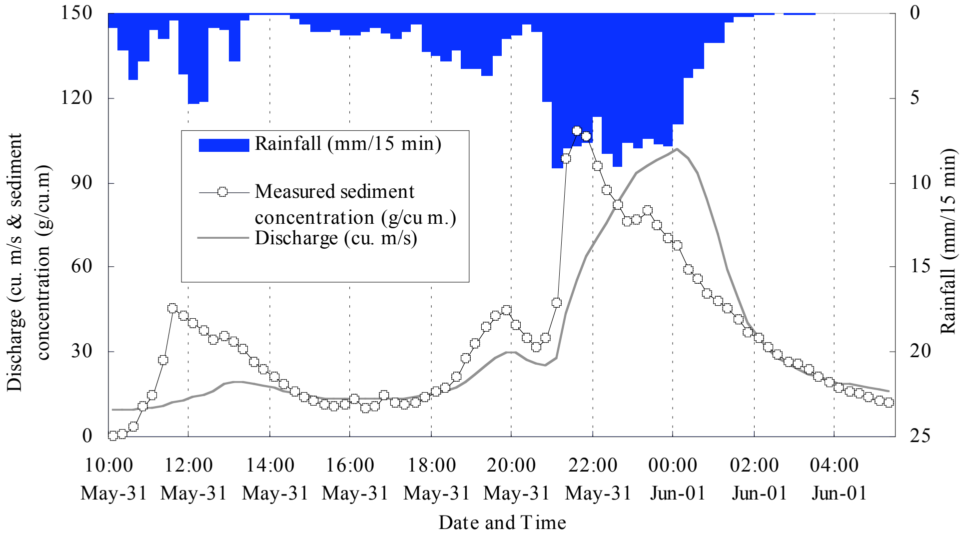


Figure 3. The sediment discharge distribution for a single rainstorm event

5. LESSONS LEARNED AND REALIZATIONS

To certain extent, the scientific objectives of the study were fulfilled. A more comprehensive erosion assessment methodology suitable for small agricultural catchment areas was developed capable of not only quantifying the total sediment yield discharged from the Todoroki River but also able to portray patterns of spatial distribution and temporal variability of erosion. In producing model outputs, simple and uniform data formats were used while ensuring that quality adequacy and availability is maintained. Although remote sensing has been identified as a key component in the model as a means to achieve a source of land cover conditions, cloud cover remain a serious constraint in obtaining a periodic source of optical data for humid regions like Okinawa. In terms of hardware resources, computational time for model execution was relatively slow. There are also critical issues in seeking cooperative arrangements with the local government as commitments are not easy to solicit because of ensuing readjustments in administrative work load and other bureaucratic implications. Also, stakeholders in the area, depending on their background often have different points of view regarding the erosion process and problem. While mitigation efforts are being enforced by the local government thru stiff penalties for excessive discharge, no quantification methodology are yet to be established. Farmers are encouraged to practice mulching but are adamant to comply because they regard this as an additional work load.

6. RECOMMENDATIONS

Transforming scientific results or academic exercises into understandable and viable management strategies remain a frontier in our experience. A critical phase to meet this challenge is the development of a user-friendly version of the model, particularly in the form of software and hardware system, while maintaining the integrity and accuracy of its estimates. Institutionalization of monitoring efforts is likewise a key issue, especially since costs are involved in maintaining the proper operation of the instruments continuously and implementation of the model in operational mode. If the local government office is tapped, training or hiring additional personnel may be an inevitable recourse since the spatial database of Todoroki watershed itself would require regular update. There may be a need to simplify a few components of the model so that field calibration and *in-situ* measurement activities are minimized and to accelerate data processing. It may not be necessary for local personnel to know the intricate details of the model but it is imperative that everyone involved knows the basics of watershed management especially since information about the Todoroki catchment and its relative importance to the Shiraho Reef ecosystem may not be widely available. Further improvements in approach, methodology and development include extending the model to possess capability to estimate nutrient discharge due to presence of heavy agricultural loads resulting from fertilizers and pesticide use. Defining future impacts of erosion on industrial and agricultural practices specifically on cropping, farming, fishing and coastal resource extraction, infrastructure management and tourism are likewise key areas of expansive investigation. At present, erosion and sediment transport mechanics for conventional farms contrasting with agricultural fields employing modern farming techniques are being examined in detail at a field scale. The long-term vision is to use the hydrological model that can be applied as a basis for drawing out maximum, allowable or tolerable load recommendations, which can for a basis for erosion control policy and enforcement, and for the formulation of a complimentary watershed and reef management plan for harmonious utilization of coastal and inland resources.

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